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LTE-A Virtual Drive Testing for Vehicular Environments

Michael Charitos¹, Di Kong¹, Jue Cao¹, Denys Berkovskyy¹, Angelos A. Goulianos¹, Tom Mizutani², Fai Tila¹,
Geoffrey Hilton¹, Angela Doufexi¹, Andrew Nix¹

Communication Systems & Networks Group

¹University of Bristol, Merchant Venturers Building, Woodland Road, Bristol BS8 1UB, UK

²Jaguar Land Rover, W/11/1 Abbey Road, Whitley, Coventry, CV3 4LF

Email: UoB: fai.tila@bristol.ac.uk, tmizutan@jaguarlandrover.com

Abstract—In this paper, a Virtual Drive Testing (VDT) methodology for a MIMO LTE Vehicle to Infrastructure (V2I) urban scenario is proposed and compared with actual road drive tests. We have developed a unique and generic radio performance analysis process based on 3D ray traced channel models, theoretic or measured antenna patterns, RF channel emulation and hardware-in-the-loop radio measurements. A 3D ray-tracing channel model is used to predict the spatial and temporal multipath ray components of the radio propagation channel between an LTE BS and the vehicle. Measured LTE vehicular antenna patterns were then applied using a spatial and polarimetric convolution process. The resulting channels were streamed into a Keysight PropSim F8 channel emulator, which was programmed to communicate with the multi-channel LTE BSs emulator and a Samsung S5 mobile client performing a handover procedure. The VDT emulation method proposed in this paper is shown to be reliable and repeatable and the accuracy of the emulated throughput agreed well with real measurements for MIMO operation.

Keywords—LTE, MIMO, V2I, Handover, Emulation, Ray Tracing channel model

I. INTRODUCTION

Vehicular communications demand high data rates with minimum level of latency in dynamic environments in order to serve high mobility applications. It is expected that vehicles will communicate with other vehicles and infrastructure using a number of different wireless technologies, including DSRC/802.11p, LTE and in the future mmWave. LTE is one of the most promising wireless broadband technologies that can reliably provide high data rate to mobile users. Like all cellular systems, it benefits from a large coverage area, high penetration rate, and high-speed terminal support. Cellular LTE systems with multiple-input multiple-output (MIMO) antenna techniques can reach data rates from 50Mbit/s up to 1Gbit/s in LTE-A depending on the MCS (modulation and coding schemes) [1-2].

Channel emulation is typically used to evaluate performance in realistic situations. In this paper, a fading channel emulator (Keysight PropSim F8) [3] and an LTE base station emulator (R&S CMW 500) [4] are used to evaluate LTE-A performance

on selected vehicular urban routes. With the aid of a channel emulator the simulation environment can be controlled. Furthermore, the tiresome task of performing successive field measurements is limited to the minimum and the rest of the experiments are carried out inside a testing lab.

Here, a new method for virtual drive testing (VDT) for Vehicle-to-Infrastructure (V2I) applications over MIMO LTE vehicular scenarios that is using Bristol's unique 3D ray-tracing channel modelling tool is proposed. An appropriate drive route is selected through the available geographic database of Bristol and then a virtual car was driven around the chosen test route. A detailed channel structure was modelled between two LTE BSs and the vehicle. The predicted channel matrices were generated using measured 3D antennas for the BS and vehicle respectively. Finally, the resulting channels were streamed into the Keysight PropSim F8 channel emulator [3], which was programmed to communicate with a multi-channel LTE BS emulator (a Rohde & Schwarz CMW500) [4] and a Samsung S5 mobile client.

The remainder of this paper is organized as follows: In Section II, the description of the channel modelling and the antenna radiation patterns is provided. Section III presents the simulation parameter settings, together with the proposed configuration setup of the conductive system. Section IV analyses the performance evaluation results of both the VDT and the road drive tests followed by the key conclusions of the presented work in Section V.

II. Channel Generation and Antennas Configuration

A. Overview of the Ray-tracing Tool

The spatial and temporal multipath ray components of the radio propagation channel between the LTE BS and the vehicle are modelled using the University's unique 3D outdoor ray-tracing tool [5], [6]. The ray-tracing engine identifies all possible ray paths between the transmitter and the receiver in 3D space, up to a cut-off threshold of -120 dBm. The database includes terrain, buildings and foliage, all represented at a resolution of 10m. Figure 1 illustrates a snapshot of the ray tracing implementation for a point-to-point link example over the selected route within

the geographical map of Bristol's city centre. The rays are colour-coded according to the received power at the user, with the lightest colours referring to the strongest ray paths. The ray-tracing deterministic model has been validated for cellular and microcellular applications, where the transmitter is located above or well below the rooftop level at frequencies of 800MHz [7].

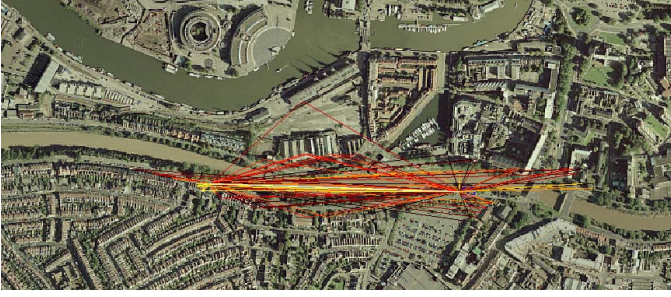


Fig. 1. Point to point ray-tracing and the resulting rays between BS and User

B. Channel Modelling

In order to compute a set of wideband channel matrices suitable for OFDM modelling, the procedure reported in [8] was followed. Point-source 3D ray-tracing was performed from the BS to each vehicle location. This provided information on the amplitude, phase, time delay, azimuth & elevation Angle of Departure (AoD) and Angle of Arrival (AoA) for each multipath component (MPC). The complex gain of each MPC was adjusted according to the transmitting (Tx) and receiving (Rx) antenna electric field (E) pattern response for the corresponding AoD/AoA and polarisation. The double-directional time-variant channel impulse response h for a link is given by the following equation [9]:

$$\begin{aligned} h(t, \tau, \Omega_{AoD}, \Omega_{AoA}) &= \sum_{l=1}^L h_l(t, \tau, \Omega_{AoD}, \Omega_{AoA}) \\ &= \sum_{l=1}^L E_l(t) \delta(\tau - \tau_l) \delta(\Omega_{AoD} - \Omega_{AoD,l}) \delta(\Omega_{AoA} - \Omega_{AoA,l}) \end{aligned} \quad (1)$$

where,

$$E_l(t) = \begin{bmatrix} E_{Tx}^V \\ E_{Tx}^H \end{bmatrix}^T \begin{bmatrix} a_l^{VV} e^{j\phi_l^{VV}} & a_l^{VH} e^{j\phi_l^{VH}} \\ a_l^{HV} e^{j\phi_l^{HV}} & a_l^{HH} e^{j\phi_l^{HH}} \end{bmatrix} \begin{bmatrix} E_{Rx}^V \\ E_{Rx}^H \end{bmatrix} e^{j2\pi v_l t} \quad (2)$$

In the above equation, $\delta(\cdot)$ represents the Dirac delta function, t is elapsed time, τ is the time-of-flight, $\Omega_{AoD}/\Omega_{AoA}$ represent the departure/arrival solid angles and L is the total number of MPCs. The l^{th} MPC is represented by h_l , which includes complex amplitude $a_l^{XY} e^{j\phi_l^{XY}}$ (2x2 matrix for all four polarisation combinations), time-of-flight τ_l , Doppler shift v_l and departure/arrival solid angles $\Omega_{AoD,l}/\Omega_{AoA,l}$. $E_{Tx}^{V/H}/E_{Rx}^{V/H}$ represent the vertical/horizontal polarisation components of the transmitting and the receiving antenna electric field radiation patterns. The Doppler frequency shift v_l is given by [10]:

$$v_l = \frac{\|v\| \cos(\omega_{AoA,l} - \omega_v) \cos(\zeta_{AoA,l} - \zeta_v)}{\lambda} \quad (3)$$

where v is the car velocity, $\omega_{AoA,l}$ is the azimuth AoA of the l^{th} MPC, $\zeta_{AoA,l}$ is the elevation AoA of the l^{th} MPC, ω_v is the car direction of travel in azimuth, ζ_v is the car direction of travel in elevation, and λ is the carrier wavelength. In the system level simulations that follow, the time-variant nature of the channel is taken into consideration by assuming that within a packet transmission the propagation channel alternates between successive OFDM symbols, due to the Doppler shifts introduced by the vehicle motion.

The produced rays are assumed to be equivalent to the MPCs of the channel impulse response. Therefore, time binning was applied to the captured rays with a time resolution equal to the inverse of the signal bandwidth. The wideband channel frequency response $G(f) = [g_1, g_2, \dots, g_N]$, where g_k represents the frequency domain channel for the k -th subcarrier, was computed using Discrete Fourier Transform (DFT)

$$G(f) = F\{h\} \quad (4)$$

The channel model can be easily extended to arrays with multiple antenna elements, accounting for a relative phase shift of each element with respect to a zero-phase reference point within the array as shown in the following equation [11]:

$$e^{j\vec{k}\vec{d}} = e^{j\frac{2\pi}{\lambda}(x^0 \sin\theta \cos\phi + y^0 \sin\theta \sin\phi + z^0 \cos\theta)} \quad (5)$$

where x^0, y^0, z^0 is the position of the antenna element with respect to the zero-phase reference point at the receiving array (similar for the transmitting side), \vec{k} is the wave vector and θ, ϕ are the elevation and azimuth angles in the spherical coordinate system of reference.

C. Vehicle and BS Antenna Radiation Patterns

Typical 3D polarimetric radiation patterns were used for both the BS and the roof-mounted vehicle antennas. The BS used a directional sector antenna with wide azimuth coverage and a narrow elevation beam, while the vehicle-based antenna was more omnidirectional in nature and housed two antenna elements in a single pod.

For the vehicle, two antennas are housed in a single pod located towards the rear of the vehicle. The vehicle-based antenna patterns are applied to the FEKO antenna simulation software. Figure 2 shows the (embedded) patterns for both antennas in terms of polarisation components and total power at 806MHz. MIMO1 is located towards the rear of the vehicle while MIMO2 is in close proximity nearer the front of the vehicle.

MIMO2 has the more omnidirectional pattern and a maximum directivity of 8dBi, while MIMO1 has a directivity of 6dBi with its main beam directed towards the rear of the vehicle. For both antennas, vertical polarisation is dominant, although there is still a reasonable amount of power (13% and 27%) in the horizontal polarisation.

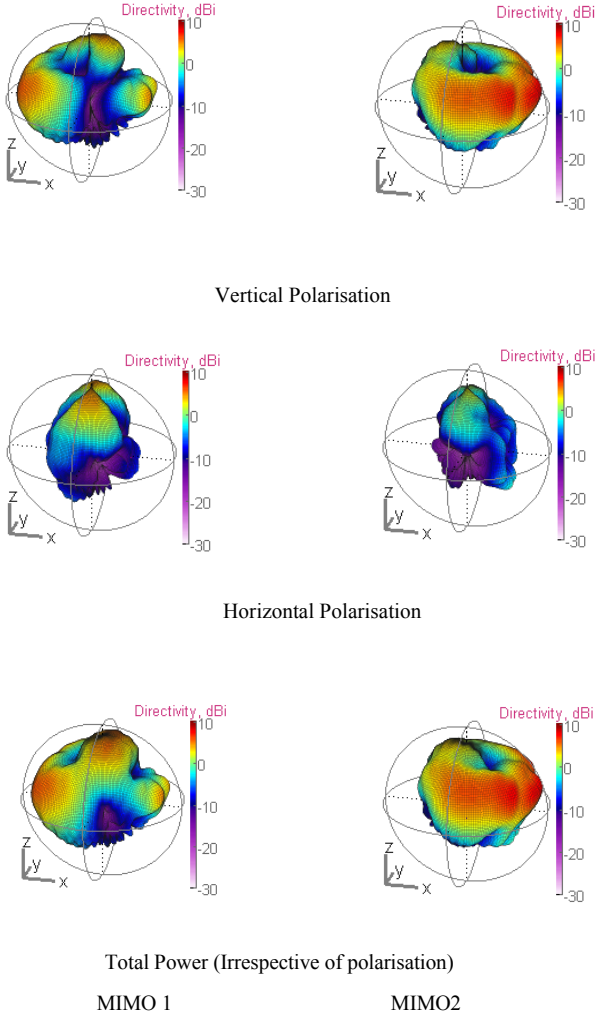


Fig. 2. Simulated radiation pattern data for vehicle antennas

III. CONDUCTIVE TESTING SYSTEM CONFIGURATION SET UP

Conductive testing is a reliable and repeatable way of verifying the performance of an integrated on-car antenna system. The emulation of the radio connection from an LTE BS to an integrated on-car antenna system uses the combination of the Keysight F8 along with antenna patterns and city-scale ray modelling as described in the previous sections.

A. System Set-Up

By conducting the RF input/output from an LTE Base station emulator (in this case a Rhode and Schwarz CMW500 Wideband Radio Communication Tester) into our Keysight F8, it is then possible to generate multipath faded signals that are representative of those observed at the output of the vehicle antenna system as it drives around our virtual city. The testbed setup is shown in Figure 3 whereas, additional circulators were required to separate the uplink and downlink during the emulation.

As UE, a commercially available Samsung S5 mobile phone equipped with an antenna connector is used to serve as the on-car radio system, and since its antennas were by-passed with SMA cables, no shielding box was used. The BS and rooftop antennas were embedded into the RF channels loaded into the emulator.

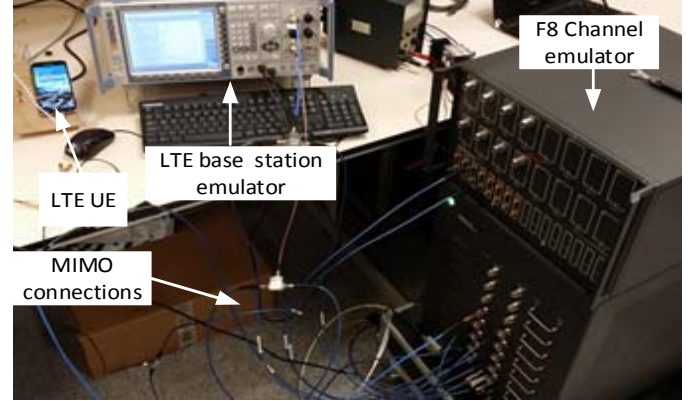


Fig. 3. Conductive LTE lab setup testing for on-car antenna system.

B. Description of the Scenario under Test

A total length of 2.7 km testing route was chosen in order to perform hardware-in-the-loop virtual drive tests, providing a representative route connecting two major points of interest within Bristol city centre. In total 1809 ray tracing location points were chosen based on the GPS logs from the drive measurements. Two Base stations (BS) were assumed to cover the selected route. The handover process was emulated as the vehicle moved from one BS region to the other. Figure 4 illustrates a snapshot of the selected route within the geographical map of Bristol's city centre.

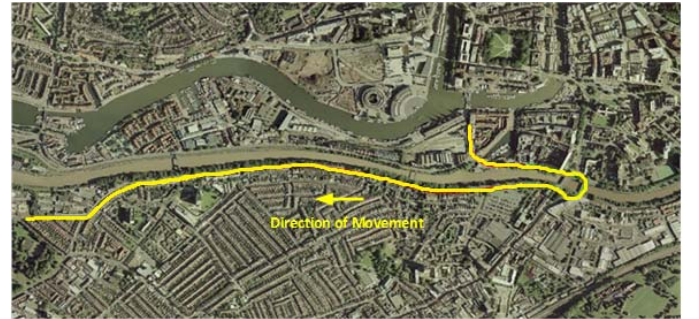


Fig.4. Bristol Test route – Handover area.

The user locations along the route were extracted from the reference measurement file. Based on the measurement data, there are 3 sector handovers for BS 1 (on the right hand side of Figure 4). A single sector was assumed for BS 2 (on the left hand side of Figure 4). The cell handover happens inside the marked area of the tested route. The BS locations were supplied by Vodafone UK under NDA thus, cannot be shown in detail in Figure 4.

A summary of the settings used in the urban test-case scenario is depicted in Table I. It should be noted that the transmit power was calibrated based on the ray tracing results and the real-world drive measurement reports.

TABLE I. LTE TEST-SCENARIO SETTINGS

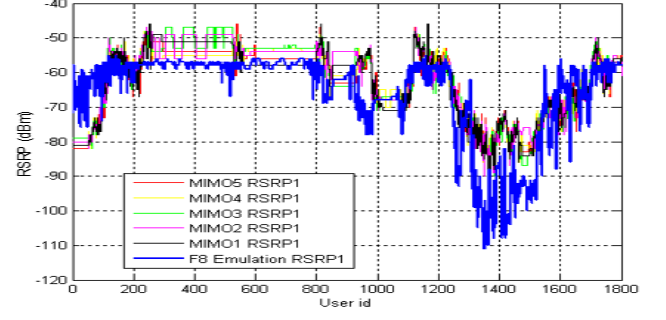
Environment Type	Urban (Bristol city-centre)
Vehicle Route Length	2.7 km
Ray-tracing points	1809
Frequency of Operation	806 MHz (LTE band 20)
Channel Bandwidth	10MHz
BS antenna type	Panel Antenna (16 dBi gain)
Vehicle antennas	MIMO1 (6dBi)
	MIMO2 (8dBi)
Receiver Sensitivity	-95 dBm
Transmit Power	34 dBm

IV. MIMO PERFORMANCE EVALUATION ANALYSIS

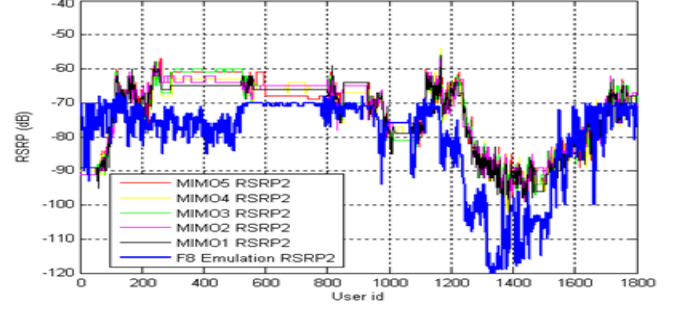
This section provides performance results of the Virtual Drive Testing (VDT) method and the Road Drive Tests obtained in the selected urban route depicted in Figure 4. A comparison between the predicted ray tracing data, the emulation output and the recorded measurement data is provided for a vehicular route in central Bristol. The study assumed the LTE 800MHz band and considered handover between two BSs. Detailed measurements incorporating the sophisticated Keysight F8 radio channel emulator are performed in the laboratory for the derivation of the radio channel dependent link quality metrics such as Reference Signal Received Power (RSRP) and Physical Downlink Shared Channel (PDSCH) throughput.

The emulated RSRP and the measurements results are presented in Figure 5 (primary and secondary antennas). The user ids (sample locations) are based on the GPS log for 1809 data samples. Handover is triggered based on UE measured RSRP values indicating the handover area close to 1400 user ids (sample location).

Figure 6a and 6b provide a comparison between the emulated results for two of the measurements (MIMO 1 and MIMO3) and the average of these two measurement runs respectively. It can be seen that the emulation follows the trend of the measurements very well. It should be noted that the throughput performance depends strongly on the channel conditions, resource allocation and the link adaptation algorithm applied by the BS, as well as the stability of the logging software. Therefore different throughput results can be observed for the same route in the real world drive tests, causing the results to vary significantly between different runs. MIMO throughput emulation results showed a peak throughput of 50Mbps. A reduction over throughput performance is observed straight before the handover point (1450m) in Figure 6b.

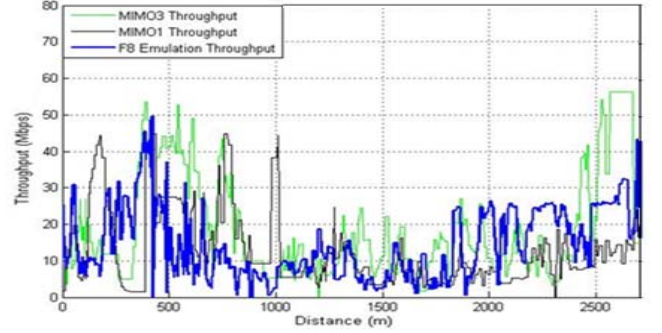


(a) RSRP1

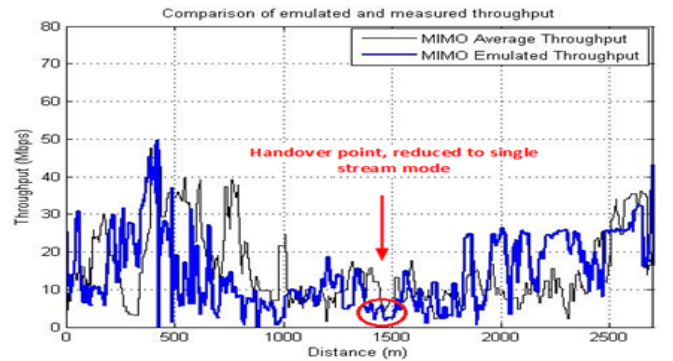


(b) RSRP2

Fig. 5. RSRP Emulation data compared with measurements



(a) MIMO measurements and emulations comparison



(b) MIMO throughput comparison with average

Fig. 6. Throughput measurements results compared with MIMO emulated throughput data.

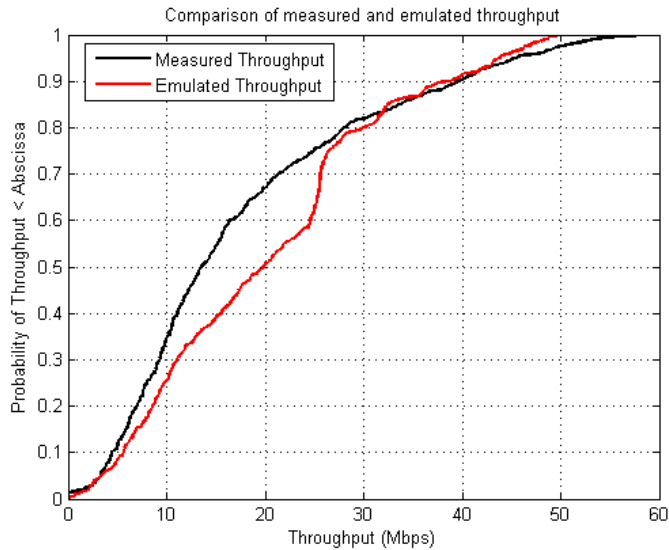


Fig. 7. CDF comparison of measured and emulated throughput

In Figure 7 a comparison of the measured and emulated throughput Cumulative Distribution Function (CDF) is illustrated. It is apparent that the suggested method is in good agreement with measured data, especially for high and low throughput values. The observed discrepancy is most due to the fact that in this work we do not consider a multiuser scenario, but rather the emulated results are based on a single user scenario where no scheduling algorithm are considered. Furthermore, the measured throughput was different for each of the two runs (MIMO 1, MIMO 3), which indicates that the throughput measured for a specific route is affected significantly by the number of users and the channel conditions observed during the measured time interval.

V. CONCLUSIONS

This paper describes a generic antenna test and radio performance analysis process by using conductive testing and emulation to perform Virtual Drive Tests for a vehicular MIMO LTE selected urban route. Geolocation maps for Bristol city centre have been incorporated into a 3D ray tracing engine.

Results indicate a good level of agreement between hardware-in-the-loop throughput results and real-world drive tests. The emulated results showed that in most cases the downlink speeds vary between 10-40 Mbps, with the maximum throughput being 50 Mbps. As expected a reduction in throughput was observed straight before the handover point. Interestingly, the road drive test throughput also varies in most cases between 10-50 Mbps.

In conclusion, the laboratory based conductive test process developed and presented in this paper was shown to be more reliable and repeatable than real-world drive tests. The accuracy of the emulated throughput agreed well with real-world measurements for MIMO operation. This new process offers a powerful and cost effective alternative to on-street testing and a number of different environments can be tested.

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